A THREE-DIMENSIONAL KINETIC MODEL FOR THE SWELLING OF INTUMESCENT MATERIALS

K.M. Butler, H.R. Baum and T. Kashiwagi
Building and Fire Research Laboratory
National Institute of Standards and Technology
Gaithersburg, Maryland 20899

An intumescent coating protects the underlying surface from fire by swelling into a thick insulating char. Design of intumescent materials has proceeded largely by systematic testing of a variety of formulations, since the mechanisms of physical, thermal and chemical behavior are not as yet well understood. Previous models of intumescent behavior [1]–[3] have treated the system as a one-dimensional heat transfer problem through a coating consisting of a char layer and a layer of virgin material separated by a thin pyrolysis zone. In this work, a fully three-dimensional, time-dependent numerical model combining the dynamics of the swelling process, the heat transfer through the coating, and the chemistry of gasification is described.

In the presence of fire, the intumescent material undergoes a series of chemical reactions that cause it to successively melt, generate a large volume of gas in a multitude of small bubbles, and eventually solidify as a multicellular insulating foam. To look at the swelling phenomenon, we first consider the dynamics of a single bubble as it expands and travels through the surrounding fluidized material. The viscosity of intumescent material is known to be a strong function of temperature, which varies considerably through the coating during exposure to fire. Under the influence of a viscosity gradient, an expanding bubble in a fluid of infinite extent feels a force in the direction of decreasing viscosity. Because the Reynolds number for the small bubbles of interest is small, the induced velocity field can be obtained analytically as a perturbation solution to the Stokes equation driven by the viscosity gradient force term. The bubble also feels a buoyancy force and pressure drag; the sum of all forces determines the net velocity of the bubble through the fluid.

Having determined the velocity field generated by a single bubble, we can now describe the swelling of the intumescent coating as the collective behavior of a large number of bubbles. Initially, the coating is represented by a rectangular volume of fluid with bubble nucleation sites randomly distributed throughout. The upper surface of the coating is exposed to a constant heat flux representing the fire source, and the temperature within the coating begins to rise. When the local temperature at a given bubble site exceeds a specified value, the bubble begins to expand. Its path through the fluid is determined by its own expansion rate, the local viscosity gradient, and the sum of the fields from all of the other bubbles, including a mirror image beneath the bottom surface to maintain the boundary condition of zero normal velocity at the rigid substrate. Bubble location and size are incremented in time according to a Runge-Kutta scheme. Merging of two overlapping bubbles is handled by replacing them with a single bubble of the combined volume located at the center of mass. The flexible upper surface of the intumescent material also feels the forces from all bubbles within the volume, and is pushed upward accordingly.

An early heat transfer model assumes simple conduction, with uniform conductivity

through the coating thickness. The detailed temperature field in the intumescent melt will eventually be solved using Lagrangian coordinates to take advantage of the simple initial geometry. The growth rate of each bubble is determined by the chemistry of gasification. An approximate expression for growth by diffusion in an oversaturated liquid-gas solution will be replaced by calculations that include the concentration of the blowing agent and local temperature and viscosity.

An example of the results from this three-dimensional model is shown in Figure 1. The upper surface is described by a grid, shown to the left, the location of whose nodes are incremented at each time step according to the instantaneous flow field. Note from the side view on the right that the bubbles near the bottom surface are much smaller than those near the top, since they have not had as much time to grow. At the time shown here, the temperature near the bottom surface is not yet hot enough to cause nucleation of the bubbles in this region.

This approach to the modeling of the dynamics and thermodynamics of an intumescent system has the attraction of providing a good physical picture of its behavior. Calculations for up to 10000 bubbles may easily be run on a workstation.

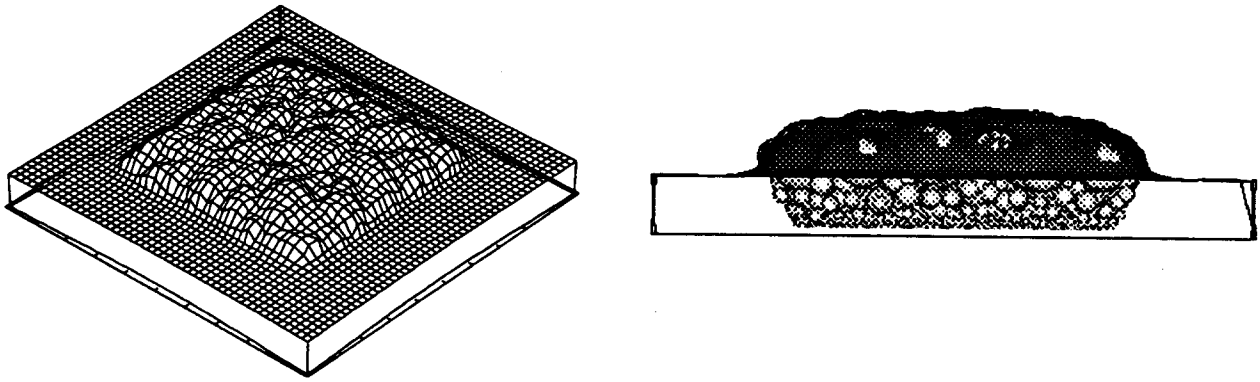

Figure 1: **Two views of an intumescent surface after development in time of 10000 bubble sites randomly distributed between (-3,3) in x and y directions in a 10×10×1 rectangular slab.**

References

[1] Cagliostro, D.E., Riccitiello, S.R., Clark, K.J. and Shimizu, A.B., "Intumescent Coating Modeling," *J. Fire & Flammability* 6:205–221 (1975).

[2] Anderson, C.E. and Wauters, D.K., "A Thermodynamic Heat Transfer Model for Intumescent Systems," *Intl. J. Engrg. Sci.* 22:881–889 (1984).

[3] Buckmaster, J., Anderson, C. and Nachman, A., "A Model for Intumescent Paints," *Int. J. Engng. Sci.* 24:263–276 (1986).